A Coupled Study of the exchange of carbon cycle gases at the surface and in the column of the atmosphere over the ARM-CART, Southern Great Plains Region

A White Paper for an NACP Intensive
December 4, 2003

Atmospheric measurements, modeling and data assimilation are poised to play a prominent role in the North American Carbon Plan (NACP). Comparison of simulated to observed atmospheric concentrations of carbon cycle gases is the only opportunity for a "top-down," quantitative evaluation of the "bottom-up" strategy for up-scaling from process studies, plot-scale flux measurements, and inventory assessments to construct regional and continental-scale inventories of the carbon cycle. Data assimilation approaches are proposed as a methodology to reconcile differences between the top-down and bottom-up assessments. All of this hinges on accurate models of atmospheric transport and measurement strategies for relating atmospheric measurements to surface exchange processes. This is not a simple matter of extending existing models of the physical climate system or numerical forecast models to include carbon cycle gases. Currently available products from NCEP (e.g., Eta, RUC) are not adequate for the task: they don't conserve mass, they have problems with diurnal/synoptic/seasonal variations in PBL depth; they don't report useful cloud-scale mass fluxes. These products are optimized for another purpose, weather forecasting as opposed to mass transport. It is unlikely that the problems with these models can be "fixed" in the near-term without degrading their usefulness as forecast models. A crucial aspect of NACP will be the development of improved high-resolution atmospheric transport models that are suitable for analyzing continuous PBL and frequent vertical profile measurements of carbon cycle gases. Models available for this task include high-resolution 3D models (RAMS, MM5, WRF), cloud-system resolving 2D models (CSRMs), and single-column GCM parameterizations (SCMs). In addition to their expected use in future weather prediction/analysis models and GCMs, we assume that tracer transport of carbon cycle gases will be added to some of these models as part of research supported by the NACP.

So how will we know the new models/analyses are any good? The answer is, we won't; unless we evaluate their performance (see for example, Confronting Models with Data, (BAMS 84, 455-469). This will require data from intensive campaigns in which we can measure atmospheric divergence and advective tendencies, PBL depth, and cloud mass fluxes and their influence on observable CO_2. To be useful for model evaluation, raw data from such measurements must be archived, analyzed and disseminated as integrated data sets for case studies that can be used to test, improve and re-test models until we get adequate performance.

The U.S. DOE Atmospheric Radiation Measurement Program Cloud and Radiation Testbed (ARM-CART) in the Southern Great Plains (SGP) arguably provides the best location in the N. America for this type of intensive NACP activity. The ARM-CART area, which approximates the size of a GCM grid cell (an area approximately 350 x 350 km in N. Central Oklahoma and Southern Kansas), is one of the most intensively instrumented regions of the world. A comprehensive suite of measurements are conducted at the surface and in the atmospheric column over the SGP region (see ARM Website and attached Appendix). The SGP site includes an outer “ring” of instrumentation designed to quantify advective inflows and outflows of mass, water, and energy over the region, a very heavily instrumented central facility, and distributed “extended facilities” across the region. Wind and temperature profiling within and above the planetary boundary layer (0.1 to 5 km) is conducted continuously. A network of surface meteorology and radiation measurement sites is complemented by surface energy flux sites, NEXRAD cloud radars and LIDARs that measure vertical profiles of water-vapor mixing ratio and several cloud- and aerosol-related quantities. The site is staffed by experienced scientists and technicians, and the Central Facility is staffed 24 hours a day. ARM SGP is a User Facility. They have conducted a number of huge and successful IOPs, and have “worked out the bugs” of data quality assurance, archival, and dissemination.

The ARM program has focused on developing and evaluating parameterizations of cloud, radiation, and precipitation processes that are used in numerical weather prediction and climate models. Modeling efforts already underway using 2D CSRMs and SCMs could be extended to include evaluation of trace gas transport, with the advantage that transport properties of operational models using these parameterizations would be documented as well. Conducting an NACP intensive at the ARM site would leverage an enormous existing investment in technology, personnel, and infrastructure that would be difficult to reproduce elsewhere.

The Southern Great Plains are well suited for carbon studies in particular because of the region's simple topography, and well characterized meteorology. Its land use patterns, soil types, planting, harvest, and yield information are all readily available. The region is also a test site for various remote-sensing satellites. With support from ARM, carbon cycle research has been initiated at SGP (see, ARM carbon cycle project and attached Appendix) and data streams are available to the broad scientific community through the ARM archives. Data products available include: continuous, high precision measurements of atmospheric CO_2 concentration; flask sampling for isotopes and trace gases from the mixed layer and free troposphere; eddy-correlation measurements of surface fluxes of CO_2, H_2O, and sensible heat over various cover types, and carbon cycle modeling of ecosystems and over the SGP domain.

To make optimal use of existing capability, new observations should focus on routine vertical profiling for trace gases from the mixed layer to the tropopause and really excellent characterization of convective mass and tracer fluxes for a few events including, boundary layer clouds, mid-latitude frontal systems and deep, precipitating convective cloud systems. This should include sampling PBL air, convective inflow, cumulus entrainment and detrainment, and environmental subsidence. This work would require the use of at least one high-speed, research aircraft capable of high-altitude missions, deployed a few times during spring and summer. Several tracers including CO_2, CO, CH_4, H_2O, radon, NOx and aerosols should be included in these measurements. Radon, for example is an inert, radioactive gas produced in the soil. Its concentration is many fold higher in the PBL than in the background upper atmosphere. Measurements of radon concentrations in the PBL and in regions of detrainment from deep convection can provide an excellent, quantitative tracer for cumulus mass flux. NOx is produced by lightening in convective storms, thus it is a good tracer for air that has been detrained from such systems. The quantity of water precipitated by a convective, precipitating cloud can be related to the water vapor content of the entrained and detrained air and the quantity of air transported. Each tracer has somewhat different properties and provides a different view of transport. Studies with a suite of tracers can provide much stronger constraints on transport than could be obtained with a single species. The data from these IOPs should be archived, analyzed, and disseminated as fully integrated data sets for case studies of surface flux and atmospheric transport modeling.

In addition to providing an essential test-bed for model development, these intensive IOPs would provide an opportunity to test important scientific questions. For example, Denning et al. (*Nature,* **376**, 240-243) have proposed that covariation of deep convection and the sign of surface CO_2 flux could result in a bias in the distribution of CO_2 flux to the atmosphere - with air influenced by respiration staying closer to the ground than air influence by photosynthesis. This, so-called "atmospheric rectifier effect" is potentially quite important for relating atmospheric CO_2 measurements to surface fluxes. The proposed studies would provide the data needed to test the rectifier hypothesis and permit us to evaluate the quantitative significance of biases in CO_2 flux estimates introduced by this mechanism. The TransCom intercomparison of inversion models has shown that differences in vertical transport due to unresolved convection and the emergent rectifier behavior of the transport models dominate the uncertainty in estimated regional fluxes in the northern midlatitudes.

In summary, one important goal of the ARM-CART intensives is to produce comprehensive case study data sets that can be used at any future time for model evaluation. At the same time, models will be available for testing as the data become available and these will play a role in developing the case studies. A second goal is to test and improve models linking atmospheric concentrations to surface fluxes. Finally, these studies will also provide a rigorous test of the bottom-up methods proposed for the NACP. The objectives of this study will be advanced by a thorough knowledge of carbon cycle of this region. At the close of this study we should know surface fluxes, stocks and carbon cycle processes in this region better than we currently do for any place else on the planet.

Specific Details of the Proposed Intensive Campaign:

Location: The study would be conducted at the ARM SGP site in Oklahoma and Kansas.
Timing: There should be several campaigns spanning the late spring to early summer (April, May, June). Early in this interval the major crop of the region, wheat will be actively growing and the surface should be a carbon sink. As this crop matures, typically in mid May, the region should transition to a carbon source. Mid-latitude temperate storms are likely early in the season and deep, precipitating convective storms are more likely as the summer approaches.

Field program design: A NACP field intensive campaign could fit naturally into ARM planning. The ARM program already employs Intensive observation periods (IOPs) as a standard method for collecting data on focused research topics. For example, IOPs often employ frequent release of sondes and higher density of data collection from profiling instruments. They typically collect profiles of winds, atmospheric water vapor and temperature, clouds and radiation. The intensive would need to add: a bottom-up effort including careful land-use/land management data (for bottom-up scaling); flux measurements in a range of representative ecosystems; routine vertical profiling for trace gases, and advective inflow/outflow of carbon cycle gases at the boundaries of the column. Continuous analyzers for CO_2 and CO would be installed on tall transmission towers located near the boundaries of the SGP site, and a network of analyzers would also be deployed on smaller towers (such as cell phone towers) throughout the site. Radon analysis systems should be deployed at some of these sites. Flask sampling during frequent vertical profiles with small aircraft near the boundaries, combined with three-hourly radiosondes and the wind profilers, will quantify inflow fluxes of trace gases. The central focus should be on excellent characterization of convective mass and tracer fluxes for a few events. This should include PBL air, convective inflow, cumulus entrainment and detrainment, environmental subsidence. A plane with high altitude (>12km) capability would be essential for this work.

Process studies/modeling activities: The primary activity of the intensive campaigns would be to conduct case studies of comprehensive measurments, archive relevant data, and integrate the data to yield products that can be used to force or to evaluate model results. This will require an explicit data integration activity with participation of both measurement teams and modelers. An example of this type of integration is provided by the Data Integration for Model Evaluation (DIME) protocols that have been developed for cloud system modeling at the ARM. In addition to atmospheric data, accurate characterization of the land surface cover is necessary to provide essential drivers models predicting land surface exchange. Part of the data collection activity would include collection and archiving of remotely sensed (e.g., hyperspectral estimates of land cover including crop type, leaf area index, and radar-based surface moisture) verified with ground-truthing.

A second activity of the intensive would be a collaborative evaluation of transport uncertainties relevant to estimates of terrestrial carbon exchange in a suite of transport models (see Randall et al., 2003 or Gurney et al., 2002, for a related example). For this purpose, a set of transport-related metrics would be derived and used to estimate model-measurement errors for the different models and case studies. The products of this intensive would hence include quantitative assessment of key uncertainties in existing models and data sufficient to drive the development of new models.

Synergy with other programs: As noted above conducting this intensive at ARM would leverage a huge investment already in place. The case studies developed here should also contribute to improvements of climate and numerical weather forecasting models. These studies of mass transport can provide additional constraints on the parameterizations used to model cloud systems. It is also significant that many of the forecast models are represented in the cloud system work being conducted at ARM. This could be a good opportunity to develop collaborations that could lead to introduction of carbon cycle processes into the forecast and data assimilation models, and would hence be of tremendous long-term benefit to carbon cycle science.

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Web URLs
http://esd.lbl.gov/ARMCarbon/
http://www.archive.arm.gov/Carbon/
http://www.arm.gov
http://kiwi.atmos.colostate.edu/group/dave/dave.html
http://biocycle.atmos.colostate.edu

Appendix I. Summary of Carbon Measurements Available for ARM SGP Region:

Most are located at ARM Central Facility. See http://esd.lbl.gov/ARMCarbon/

1. **Continuous high precision CO_2 concentrations at 2, 4, 25, and 60 m.**
2. **CO_2 isotopic ratio at 2, 4, 25, and 60 m.** Regular sampling interval is one diurnal cycle (every 3 hours for 21 h) weekly. During campaigns, sampling can be done every diurnal cycle.
3. **Carbon cycle gases and isotopes at 60 m.** Data added to NOAA-CMDL global flask network. Regular sampling interval is once per week. During campaigns, sampling can be done every day and/or night. Analysis: CO_2, CO, CH_4, N_20, H, SF_6, $^{13}CO_2$ and $C^{18}OO$.
4. **Carbon cycle gases and isotopes by aircraft at 600 m and 3600 m asl.** (ground is 314 m asl). Data added to NOAA-CMDL global flask network. Regular sampling interval is once per week. Sampling frequency can be increased or set to different altitudes. Analysis: CO_2, CO, CH_4, N_20, H, SF_6, $^{13}CO_2$ and $C^{18}OO$.
5. **Ecosystem fluxes of carbon, water, and energy at 4, 25, 60 m** (fetch of mixed croplands). Continuous measurement
6. **Ecosystem fluxes carbon, water, and energy at 4 m** (fetch of single crop field). Continuous measurement of a winter wheat-summer fallow field. During campaigns, 2 portable towers measure 2 different fields at same time. Can be moved frequently if needed.

Measurements that will be added in the next two years include:

- Continuous carbon monoxide measurements coincident with CO_2.
- Radiocarbon to identify fossil carbon sources, ground and airborne
  Permanent eddy covariance CO_2 flux at 9 agricultural sites across ARM-SGP region.
  Portable high precision CO_2 system for advection & heterogeneity determination
- Airborne continuous CO_2 concentration

Appendix II. General Arm Instruments at the Southern Great Plains

Aerosols

- **Aerosol Observation System (AOS)**
- Additional Systems:
    - **CIMEL Sunphotometer (CSPOT)**
    - **Multifilter Rotating Shadowband Radiometer (MFRSR)**
    - **Raman Lidar (RL)**

Atmospheric Profiling

- **Balloon-borne Sounding System (BBSS)**
- **Microwave Radiometer (MWR)**
- **Raman Lidar (RL)**
- **50-MHz Radar Wind Profiler and Radio Acoustic Sounding System (RWP50)**
- **915-MHz Radar Wind Profiler and Radio Acoustic Sounding System (RWP915)**

Clouds

- **Belfort Laser Ceilometer (BLC)**
- **Micropulse Lidar (MPL)**
- **Millimeter-Wavelength Cloud Radar (MMCR)**
- **Microwave Radiometer (MWR)**
- **Video Time-Lapsed Camera (VTLC)**
- **Whole-Sky Imager (WSI)**
- Additional Systems:
    - **Narrow Field of View Sensor (NFOV)**
    - **Raman Lidar (RL)**

Radiometers

- **Atmospheric Emitted Radiance Interferometer (AERI)**
- **Absolute Solar Transmittance Interferometer (ASTI)**
- **Cimel Sunphotometer (CSPOT)**
- **Infrared Thermometer (IRT)**
- **Microwave Radiometer (MWR)**
- **Narrow Field of View Sensor (NFOV)**
- **Rotating Shadowband Spectrometer (RSS)**
- **Shortwave Spectrometer (SWS)**
- **Solar Radiance Transmission Interferometer (SORTI)**
- **MFRSR-Related Instruments**
    - **Multifilter Rotating Shadowband Radiometer (MFRSR)**
    - MFR (upwelling)
- **Broad-Band Instruments**
    - **Pyranometers**
    - **Pyrgeometers**
    - **Pyrheliometers**
    - **UV-B Radiometer**
    - UV Spectroradiometer (UVS)
- **Radiometric Instrument Systems**
    - **Solar Infrared Radiation Station (SIRS)**

Surface Energy Flux

- **Eddy Correlation (ECOR) System**
- **Energy Balance Bowen Ratio (EBBR) Station**
- **Infrared Thermometer (IRT)**
- **Soil Water and Temperature System (SWATS)**

Surface Meteorology (see also Oklahoma Mesonet and Kansas Mesonet)

- **Chilled Mirror (CM)**
- **Surface Meteorological Observation System (SMOS) Instruments**
- **60-m Tower; Temperature and Humidity Sensors**